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An Example of Application of Entropy: Food Science from Entropic Point of View

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Abstract

The concept of entropy appears to be one of the most difficult ones to understand for students in junior university courses. In order to facilitate comprehending the concept of entropy and its usefulness, it is desirable to provide a few concrete applications. In the present article, '*food science from entropic point of view*' has been chosen as an example, where we emphasize, in particular, that the concept of entropy can also play an important role in food science. We point out that, from entropic point of view, ideal foods should satisfy the following two conditions: 1) they should possess entropy as low as possible so that their molecular structures are highly ordered and 2) they should actively participate in biochemical reactions which pump out the produced entropy outside the body.

1. Introduction

The concept of entropy, which is dealt with in the fields of thermodynamics and statistical mechanics of physics or chemistry, is one of the most difficult ones for students to grasp. The reason is because this concept is usually introduced in rather formal and abstract manner and its applications are often limited only to physically idealistic cases. Therefore, in order to make students understand and recognize the usefulness of this fundamental concept, it is important to introduce some examples of its applications to well-known phenomena or problems after theoretical introduction of the concept. '*Entropic view on problems of resources and environment*'[1], '*entropy in economy*'[2], '*culture and entropy*'[3] and so forth can be as such good examples. In the present paper, however, we introduced '*food science from entropic point of view*' to be one of the examples of its applications.

2. Maintaining low entropy in organic system

Today much attention is paid on foods from various points of view such as gourmet, healthy foods, diet and etc. Food science is now making rapid progress under the influence of modern biotechnology. For example, the species of foods known from ancient time are being thoroughly studied from scientific point of view and new type of foods such as functionality foods[4] are being actively developed responding thus to the various demands of the society.

Regarding dietary life, it has been often considered that caloric intake, i. e., energy balance, is most fundamental. Along the line of this view, extensive studies have been performed in the field of nutrition and food science. However, to the knowledge of authors, there have been only limited studies on food science from physics point of view. It is E. Schrödinger who for the first time pointed out the most essential physics on food science. He argued, in his book '*What is life*'[5] published in 1944, that '*Living organism eats negative entropy (negentropy) to conserve its life*' and stressed the importance of entropic view in understanding the essence of life. It seems as if living organism does not obey the second law of thermodynamics which states that '*all the phenomena (in isolated system) inevitably go towards the direction in which entropy increases.*' Since a living being exists in a stationary state, average change of incoming energy E_i in time and that of outgoing energy E_o should be balanced in a body, i. e.,

$$dE_i/dt = dE_o/dt. \tag{1}$$

Therefore, the mechanism of sustaining life, which is a non-equilibrium state, does not exist solely in the metabolism of energy. Schrödinger paid attention to the balance of entropy S in a living body and expressed the net entropy change incepted by a body in time dS_n/dt as

$$dS_n/dt = dS_i/dt - dS_o/dt = -(dS/dt)_{irr} < 0. \tag{2}$$

Since a living organism exists in a non-equilibrium state where irreversible reactions take place, the produced entropy in a body must be compensated by '*negative*' intake entropy. Schrödinger expressed this as '*organic system eats negentropy*'. One should note that entropy of ingesta is low compared to its energy while that of excreta is high compared to its energy. It comes out from his theory that it is energy of high quality, i.e. with low entropy, that is most necessary for preserving life (i.e., preserving the state far away from thermal equilibrium which has maximum entropy.) It can be easily understood that indeed ingesta possess lower entropy than excreta, if one compares the real content of the ingesta (intake food) with that of the excreta (waste substances plus discharged calorie). (In the case of animals, the main ingredients of excreta are carbon dioxide and water which are produced by oxidation of carbon and hydrogen contained in foods. These are mainly evacuated by respiration.)

As is well known, the entropy S can also be expressed in terms of the number of possible microscopic states as follows, when the energy, volume and the number of particles of the system are given:

$$S = k \log W \quad (k: \text{Boltzmann constant}). \tag{3}$$

The higher the entropy is, the more (exponentially) the states are disordered. In this sense the entropy is an index of disorderedness. The concept of entropy is also used in information science. The '*information entropy*' is related to the amount of information through an equation similar to eq. (3). Thus the entropy has a close relation to the concepts of order, disorder and/or information. The change of structures in organic molecules contained in foods (such as functionality foods) also can be treated quantitatively by using the entropic change. Foods are the source of energy of activity, and, at the same time, provide negative entropy for restoring order in an organic system. Therefore, ideal foods should satisfy the following two conditions in addition to having an adequate calorie level: 1) Ideal foods should have entropy as low as possible so that their molecular structures are highly ordered and 2) such foods should actively participate in biochemical reactions which pump out the produced entropy outside the body. Various types of vitamins, minerals and foods containing dietary fibers are considered to satisfy partially these conditions. Today, the so-called functionality foods are being developed extensively. We think that the entropic point of view can be useful in this field as well and can shed new light on food science.

The rest of the article is devoted to general consideration on foods from an entropic viewpoint.

3. The origin of foods —— the sunlight carrying low entropy

We, mankind, existing in the '*living*' atmosphere of the earth enjoy in obtaining the benefits of energy from the sun. From physical standpoint, however, the fact that the sunlight possesses low entropy is more important than considering it simply from energy viewpoint[6]. In considering vegetable foods, it is necessary to clarify the physical mechanism of photosynthesis of plants. As is known, photosynthesis comprises the process of synthesizing glucose from carbon dioxide and water, in which the sunlight plays important role (Fig.1). Through the process, the energy of sunlight possessing low entropy is trapped or fixed in glucose.

In other words, "*the order is synthesized*" in organic molecules via this process could be illustrated as follows:

$$6\,H_2O + 6\,CO_2 + 48\,h\nu\,(\text{photons}) \xrightarrow{\text{chloroplast}} C_6H_{12}O_6 + 6\,O_2$$

Fig.1

In chloroplast in general, the photosynthesis takes place by the light (photons) having wavelength shorter than 700 nm. There exists minimum energy required to excite the chlorophyll by absorbing photons. Fig.1 explains that it needs 48 photons to synthesize one glucose molecule from carbon dioxide and water molecules.

In this reaction, 0.62 eV out of 1.77 eV of the photon energy is stored in a glucose molecule while the rest energy of the photon, 1.15 eV, is utilized to discharge entropy as waste heat, which is produced in this irreversible process. The glucose and the oxygen which are the products of the process absorbed 48 photons and hence possess the energies higher than those of the raw materials, i.e. carbon dioxide and water. Although, there is no big difference between the entropy of the products and the materials, one can say that the products have relatively low entropy compared with their energy since these products possess higher energy. Now, let us calculate the entropy balance[6], assuming that photosynthesis takes place at temperature 25°C. As a photon (scattered light) has the entropy of 1/1300 K per unit energy, incoming entropy per one glucose molecule is calculated as,

$$\begin{aligned} & 48\times(1.77\,\mathrm{eV}/1300\,\mathrm{K}-1.15\,\mathrm{eV}/298\,\mathrm{K}) \\ = \; & -0.120\,\mathrm{eV/K}=-1390\,k. \end{aligned} \tag{4}$$

Thus, the equation of entropy balance for photosynthesis can be written as

$$\begin{aligned} & C_6H_{12}O_6+6\,O_2-6\,H_2O-6\,CO_2 \\ = \; & [48\,h\nu-\text{waste heat}]+[\text{entropy production by irreversible process}]. \end{aligned} \tag{5}$$

Then, equation (5) yields

$$-70\,k=-1390\,k+1320\,k. \tag{6}$$

In eq. (6), 1320 k is the amount of entropy produced in the irreversible process of photosynthesis and others, which is thrown away outside.

The efficiency of energy conversion in photosynthesis is considerably good. It is called biomass that makes use of this characteristic to produce fuel-like alcohol from the plants growing rapidly.

Next, we consider about animal foods. In nature, since animals cannot create energy with low entropy by themselves, they take it from glucose synthesized by plants. The negentropy partaken from plants is partially fixed in herbivorous animals and is utilized subsequently by carnivorous animals. In this way, by food chain, the lowness of entropic value of sunlight is utilized sequentially. As entropy is produced at every step of chain, fewer animals can be fed at later steps in food chain. (These animals were turned into fossil fuel after their death in the end of the Mesozoic era. Thus we see that only a small part of high quality (i.e., low entropy) sunlight energy was fixed in the fossil fuel.)

4. Mechanism of keeping low entropic state

In order to maintain the stationary state of organic system, the energy flow of incoming energy and outgoing energy has to be balanced (see eq. (1)). Since in general the incoming energy carries its entropy, it is indispensable for a living organism to take energy with low entropy and dispose energy with high entropy so as to evacuate the entropy produced in the body (Fig.2). The net entropy has to be negative as can be seen from eq. (2).

glucose → oxygen → (substances containing lower energy)	Electro-chemical energy is released through the reactions thus temperature increases	→	thermal energy +water +carbon dioxide (substances containing higher energy)

incoming energy change = outgoing energy change

$$dE_{\mathrm{i}}/dt = dE_{\mathrm{o}}/dt.$$

incoming entropy < outgoing entropy

$$dS_{\mathrm{i}}/dt < dS_{\mathrm{o}}/dt.$$

Fig.2

5. Conclusion

We have presented a general macroscopic entropic view on food intake. If one wishes to develop further microscopic viewpoint of entropy to actual foods, one needs to know the structure and content of organic substances contained in foods as well as the quantities such as activation entropy and/or entropy change in biochemical reactions taking place in a body and then such quantities must be calculated on the basis of reaction rate theory. One should also take into account the dependence of these values on temperature and density. Unfortunately, we are not familiar to what extent such thermodynamical and chemical considerations were developed until now. Today, however, with the help of computer, simulation of various chemical reactions or even design of diverse organic compounds (based on quantum mechanics) became available thanks to the achievements in organic chemistry and biochemistry. Taking such progress into consideration, the above-mentioned approach seems to be accessible in principle. At least the consideration based on mathematical model may exist as well.

We have shown that the entropic approach can be effective to food science as well. In concluding the paper let us hope that the entropic approach will give us new insight and stimulus to the studies of new types of foods such as functionality foods which are now under active progress. At the same time, we wish that the entropic approach to food science presented in this paper will serve as an example which helps students getting familiar with this abstract concept.

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